arXiv:hep-ph/9505207v1 2 May 1995

A Global Fit of LEP/SLC Data with Light Superpartners

G.L. Kane[1], Robin G. Stuart[2], James D. Wells[3]

Randall Physics Laboratory, University of Michigan,
Ann Arbor, MI 48109–1120, USA

Abstract

We find that re-analyzing the LEP/SLC data with light superpartners and low $\alpha_s(m_Z^2) \simeq 0.112$ yields a better fit to the data than the Standard Model, gives a satisfactory description of the R_b measurement, and gives a better fit to A_{LR}. A large body of low energy ($q^2 \ll m_Z^2$) data and analyses provide compelling evidence for $\alpha_s(m_Z^2) \simeq 0.112$. Global fits to LEP/SLC data in the Standard Model, however, converge on a value of $\alpha_s(m_Z^2) \simeq 0.126$. Recently it has become increasingly clear that these should be viewed as incompatible rather than values that can be averaged. We investigate the possibility that new physics is causing the LEP high value. To this end we have conducted a global analysis of LEP/SLC data in the Standard Model and also in the Minimal Supersymmetric Standard Model. Several predictions could confirm (or rule out) the results of this paper: light chargino and stop, top decays into stop and neutralino, large R_b, large A_{LR}, and a higher M_W. We briefly discuss the implications of low α_s for more fundamental high-scale supersymmetric theories.

[1] gkane@umich.edu
[2] stuart@thoth.physics.lsa.umich.edu
[3] jwells@walden.physics.lsa.umich.edu

Introduction

Recently it has become increasingly likely that there exists a genuine and tantalizing discrepancy between low energy ($q^2 \ll M_Z^2$) determinations of α_s and the value of α_s extracted from LEP/SLC data at the Z-peak. Shifman [1] has argued persuasively that the high value of $\alpha_s(m_Z^2) \simeq 0.126$ obtained by fits to $q^2 = m_Z^2$ data is incompatible with the values of $\alpha_s(m_Z^2) \simeq 0.112$ extracted from low energy observables and run up to the Z scale. Indeed, graphical demonstrations [2] of all the various determinations of α_s clearly show an apparent systematic separation of $\alpha_s(m_Z^2)$ between the low energy data and the Z-peak data.

In this letter we will assume as correct the plethora of extremely precise [3] low energy determinations of $\alpha_s(m_Z^2) \simeq 0.112$. Then the extracted $\alpha_s(m_Z^2)$ from LEP/SLC must either settle to a lower central value with more statistics, or there is a systematic effect which causes LEP/SLC to fit to an inaccurately high value of $\alpha_s(m_Z^2)$. Our primary goal in this letter is to investigate whether $\alpha_s(m_Z^2)$ extraction in a supersymmetric model can be substantially lower than the value of $\alpha_s(m_Z^2)$ determined from Standard Model fitting procedures, thus reconciling low energy and Z-peak determinations of $\alpha_s(m_Z^2)$.

One way to think of this is as follows. The LEP/SLC data has been analyzed assuming the Standard Model is correct. If instead light superpartners exist, then a new analysis of the data is required. All output quantities will change. In particular, we find that $\alpha_s(m_Z^2)$ is allowed to decrease by about 0.01; R_b is now more consistent with the experimental data; agreement with A_{LR} is better; and in general the global fit to the data is good. A number of other authors have also noted that if R_b is explained by new physics, then α_s will decrease (See for example Refs. [1, 4, 5]). Before such an argument can be taken seriously, it is necessary to show that it is quantitatively large enough and also that it does not contradict other observables such as left-right asymmetries, forward-backward asymmetries and M_W. We have explicitly demonstrated these features.

Gauge coupling unification and low α_s

Before continuing further, we should digress on a related question: Is $\alpha_s(m_Z^2) \sim 0.112$ compatible with simple grand unified theories? One of the early successes of supersymmetric grand unified theories was their ability to unify the gauge couplings (e.g., in $SU(5)$) and *predict* values of $\sin^2 \theta_W$ and $\alpha_s(m_Z^2)$ which were in accord with experiment. As the data and analyses got better, and the errors several times smaller, most upper limits on mea-

sured $\alpha_s(m_Z^2)$ started to drop. Simultaneously, supersymmetry model builders refined their calculations and the theoretical lower limits on the predicted $\alpha_s(m_Z^2)$ rose. As it stands today, the lower limit on $\alpha_s(m_Z^2)$ is 0.126 in a simple SUSY GUT theory [6] (no GUT scale threshold effects, intermediate scales, or non-renormalizable operator effects) with common scalar and gaugino masses, and squarks bounded below $1\,\mathrm{TeV}$. While this lower limit is compatible with the quoted [7] $\alpha_s(m_Z^2)$ from LEP/SLC data, it is not compatible with $\alpha_s(m_Z^2) \simeq 0.112$.

An $\alpha_s(m_Z^2)$ crisis is actually welcome because it demonstrates that we can learn about high–scale physics from weak–scale data. It leads us away from minimal models such as the CMSSM [8] which assume common scalar masses, common gaugino masses, and precise gauge coupling unification with a desert between the weak scale and the unification scale. This minimal constrained supersymmetric model cannot produce $\alpha_s(m_Z^2)$ below 0.126 or R_b above about 0.2168; it is a very predictive model. GUT scale threshold effects and non-renormalizable operators both modify [9, 10] simple notions of gauge coupling unification based on a continuous running of beta-functions from the low scale to the high scale, as do effects at intermediate scales that do not affect the perturbative unification [15]. As low energy data gets better it starts to resolve gauge coupling palpitations near the unification scale. Several authors [6, 11] have used the lower $\alpha_s(m_Z^2)$ values to get insight into the form of possible supersymmetric GUT theories. This is in stark contrast to non-supersymmetric GUTs which have extreme difficulty rectifying the very large first-order problems of gauge coupling unification and proton decay constraints with second-order threshold corrections [12], as well as keeping the weak scale and unification scale naturally separate.

It has been suggested [13] that if one simply abandons the common gaugino mass assumption then low values of $\alpha_s(m_Z^2)$ can be obtained. While we fully agree with Ref. [13] on the importance of resolving this α_s "crisis", this is a dramatic approach, and a testable one. It is disquieting because in a simple GUT theory the gauginos must unify in a single adjoint representation of the GUT gauge group to preserve the gauge symmetry. If common gaugino masses are discarded then gauge coupling unification also seems to be gone. In string theory, however, it is possible to have gauge coupling unification without having a grand unified group in four dimensions [14]. Usually it is assumed that the gauginos will unify as well but this is not necessarily required. What is required is the raising of the unification scale from the typical scale of 10^{16} GeV where simple SUSY theories want to unify, up to the string scale $\sim 10^{18}$ GeV. This is a non-trivial task [15], requiring the introduction

of additional states which affect the running of the gauge couplings. For these reasons, results based on simple GUT gauge coupling unification without gaugino mass unification are difficult to obtain in a theory.

In this letter it is not our purpose to promote any specific notions of the GUT scale theory, and we do not attempt to provide any additional insight into how a more fundamental high-scale SUSY theory could *predict* a low $\alpha_s(m_Z^2)$. We shall focus instead on the low energy data, and demonstrate how fits to LEP/SLC Z-peak observables with light superpartners could give lower $\alpha_s(m_Z^2)$ than fits without superpartners. We know that by combining intermediate scales [15], which do not hurt perturbative unification, with high scale threshold effects [6, 11] we can construct a theory with the couplings and spectrum that we find in this work.

Extracting α_s in the Standard Model

The values of $\alpha_s(m_Z^2)$ at the Z-peak are extracted, mainly, from two classes of observables: Γ_{had} and jet event shapes. The most important observables in the Γ_{had} class are Γ_Z, $R_{\text{lept}} \equiv \Gamma_{\text{had}}/\Gamma_{\text{lept}}$, and σ_{had}. The fits for $\alpha_s(m_Z^2)$ in the two approaches yield [7, 16, 17],

$$\alpha_s(m_Z^2) = 0.126 \pm 0.005 \quad \text{from } \Gamma_{\text{had}} \text{ observables, and}$$
$$\alpha_s(m_Z^2) = 0.119 \pm 0.006 \quad \text{from jet event shapes.}$$

The error in the $\alpha_s(m_Z^2)$ determination from Γ_{had} observables is statistics limited. The error associated with the jet event shape measurements is mostly theoretical, since the non-perturbative effects of hadronization must be folded into the perturbative parton level jet correlations. Furthermore, the perturbative QCD calculations for the event shape measurements [18, 19] are not universally agreed upon, which compounds the uncertainty. We therefore cautiously ignore the jet event shape determination, which are in any case only 1σ from the low values, and concentrate on the Γ_{had} observables.

In an effort to analyze all observables at LEP simultaneously in the Standard Model and in the minimal supersymmetric model we have implemented supersymmetric loop corrections in ZOPOLE [20] and interfaced it with the CERN library minimizer MINUIT [21] for a complete χ^2 fitter. The observables that we use in our χ^2 fit are $\mathcal{O}_i = \Gamma_Z$, σ_{had}, R_b, R_c, A_{LR}, A_{FB}^b, A_{FB}^c, $R_{\text{lept}} \equiv \Gamma_{\text{had}}/\Gamma_{\text{lept}}$, and A_{FB}^{lept}. Next we fix the Higgs mass to a low value consistent with supersymmetry ($m_h = 100\,\text{GeV}$), and let MINUIT find the minimum χ^2 for

4

M_t and $\alpha_s(m_Z^2)$. The χ^2 is defined as

$$\chi^2 \;\; = \;\; \sum_i \frac{(\mathcal{O}_i^{\text{theory}} - \mathcal{O}_i^{\text{expt}})^2}{(\Delta \mathcal{O}_i^{\text{expt}})^2}.$$

All the values of $\mathcal{O}_i^{\text{theory}}$ are calculated within a specific model and the better the match between theory and data the lower the χ^2. Using the Standard Model we find

$$M_t \;\; = \;\; 167 \pm 15 \,\text{GeV}$$
$$\alpha_s(m_Z^2) \;\; = \;\; 0.123 \pm 0.005$$

as the results of our χ^2 fit to the observables. These results are consistent with the fits obtained by the LEP Electroweak Working Group [7] corrected for a light Higgs.

Extracting a lower α_s in supersymmetry

Now we set $\alpha_s(m_Z^2)$ to a smaller value (we choose 0.112) consistent with the numerous low energy observables, and map out the supersymmetric parameter space which yields a *better* χ^2 with superpartners in loops and $\alpha_s(m_Z^2) = 0.112$ fixed than does the Standard Model, whose χ^2 minimum is at $M_t = 167 \,\text{GeV}$ and $\alpha_s(m_Z^2) = 0.123$.

The idea that light superpartners might resolve the $\alpha_s(m_Z^2)$ discrepancy between high scale and low scale data is hinted at by the large measured value of $R_b \equiv \Gamma(Z \to \bar{b}b)/\Gamma(Z \to \text{had})$ which is approximately 2.3σ from the Standard Model prediction. It was found in Ref. [22] that if $m_{\tilde{t}_1}$ and $m_{\chi_1^+}$ were both less than about $110 \,\text{GeV}$ then the discrepancy between theory and data for this one observable could go away. Since R_b had the highest "pull" on the Standard Model χ^2 for LEP data, resolving this 2.3σ deviation could substantially improve the global fit.

If the theoretical prediction for R_b is raised by increasing the $\Gamma_{\bar{b}b}$ partial width, then for a fixed α_s the total hadronic decay width is also increased. To a good approximation the hadronic width of the Z is separable into an electroweak piece and a QCD correction:

$$\Gamma_{\text{had}}^{\text{theory}} \;\; = \;\; \Gamma_{EW,\text{had}}^{\text{theory}} \left(1 + \frac{\alpha_s(m_Z^2)}{\pi} + \cdots \right) \Longleftrightarrow \Gamma_{\text{had}}^{\text{expt}}$$

Although R_b is rather insensitive to the QCD corrections, the partial widths $\Gamma_{\bar{b}b}$ and Γ_{had} are quite sensitive. It is clear from the above equation that if we obtain a higher $\Gamma_{EW,\text{had}}^{\text{theory}}$ in supersymmetry than was found in the Standard Model then the QCD corrections must be smaller in the supersymmetric theory to match the experimental determination of $\Gamma_{\text{had}}^{\text{expt}}$;

that is, $\alpha_s(m_Z^2)$ must be lowered to best fit the data. Therefore, it qualitatively appears that we can simultaneously increase R_b and lower α_s, while at the same time keeping $\Gamma_{\text{had}}^{\text{theory}}$ fixed.

Our next step then is to hone in on the region of supersymmetric parameter space which will substantially increase R_b [22] and check to see that the χ^2 fit to LEP/SLC data is consistent with low $\alpha_s(m_Z^2)$ and *all other observables* such as A_{FB}, Γ_Z, R_{lept}, etc. With light superpartners having a large effect on observables such as R_b, one would expect *a priori* that these same superpartners will affect other observables at LEP and potentially could yield a worse χ^2 fit to the data than the Standard Model. It is imperative that all observables be analyzed simultaneously to confidently state that a lower α_s extraction at LEP is possible in supersymmetry. To be precise about our procedure, we have fixed $\alpha_s(m_Z^2) = 0.112$ and searched through the MSSM parameter space for solutions which yield *better* χ^2, at fixed $\alpha_s(m_Z^2)$, than the lowest χ^2 fit in the Standard Model where $\alpha_s(m_Z^2)$ was allowed to vary to its best-fit minimum value of 0.123.

We have fixed $\alpha_s(m_Z^2) = 0.112$ for two reasons. One, we want to see if χ^2_{SUSY} at a low value of $\alpha_s(m_Z^2) \simeq 0.11$ can give a better χ^2 than the Standard Model. And, we have determined that $\alpha_s(m_Z^2) = 0.112$ is near the best minimum χ^2_{SUSY} in this analysis (with heavy first and second generation squarks and sleptons). Due to the extremely complicated minimization procedure with all the free MSSM parameters we do not yet claim with certainty that the global minimum of the χ^2_{SUSY} fit is at $\alpha_s(m_Z^2) = 0.112$, but only that there are at least local minima with $\alpha_s(m_Z^2) = 0.112 \pm 0.004$ and $\chi^2_{SUSY} < \chi^2_{SM}$. Furthermore, we have fixed $\tan\beta$ at its lowest possible value, which is determined by the top Yukawa remaining perturbative below the GUT scale, since this value gives the best χ^2_{SUSY} in the region of $\tan\beta < 30$. For $\tan\beta > 30$ the light pseudo-scalar Higgs can become important and we have not yet incorporated it into ZOPOLE.

We have included into ZOPOLE all vector boson self-energy diagrams and vertex corrections which involve the charginos, neutralinos, stops and sbottoms. The only light squark or slepton expected in the spectrum which will affect our analysis is the $\tilde{t}_R$, which becomes light through mixing in the stop mass matrix. Since the sbottoms are isospin partners to the stops they must be explicitly included in the calculation. We expect and assume that all other sparticles have masses too large to have a significant impact on the final answer. Although we work basically in a minimal supersymmetric theory, our results are largely independent of the gluino mass, and of first and second family squark masses if they are at all heavy. Results do assume $M_1 = M_2$ (bino and wino masses) at the GUT scale. Other

Figure 1: Region of supersymmetric parameter space with a better χ^2 fit with $\alpha_s(m_Z^2) = 0.112$ than the best standard model χ^2 fit which was at $\alpha_s(m_Z^2) = 0.123$.

Figure 2: Four observables versus the lightest chargino mass. The dotted line is the measured central value of the observable, and the dashed lines are the 1σ limits. The solid straight line is the Standard Model best fit value obtained from ZOPOLE with $m_h = 100\,\text{GeV}$, and the shaded region that which yields $\chi^2_{SUSY} < \chi^2_{SM}$ as other parameters are varied. As expected in a better χ^2 fit, the R_b and A_{LR} predictions fit the experimental values as measured by LEP/SLC better than the SM does. Note also that the W mass prediction in supersymmetry is higher than the Standard Model prediction. And, the top is expected to decay into the lightest stop and light neutralinos with branching fraction as high as 60%.

parameters are varied over allowed values (rather than guessed), to give the regions in the figures.

Our calculations of the one-loop diagrams were checked in ZOPOLE by exact numerical cancellations of the $\log(\mu^2)$ which accompany all divergences in counter terms of the on-shell renormalization scheme. These exact cancellations of the $\log(\mu^2)$ in all observables and Δr are crucial requirements for a trustworthy calculation.

Figure 1 is a summary of the main result in this letter. The enclosed area in the $m_{\chi_1^+} - m_{\tilde{t}_1}$ plane is the region of parameter space which yields a better χ^2 fit to LEP/SLC data using supersymmetry and $\alpha_s(m_Z^2) = 0.112$ than the absolute lowest χ^2 obtained in the Standard Model (with $\alpha_s(m_Z^2) = 0.123$). The SUSY $\chi^2/\text{d.o.f}$ are as much as $1/3$ better than the Standard Model best fit, and this minimum occurs when the chargino is near $80\,\text{GeV}$ and the stop is near $60\,\text{GeV}$. Interestingly, the lower bound on the lightest chargino is about $58\,\text{GeV}$ although high R_b values were obtained for $m_{\chi_1^+} < 58\,\text{GeV}$. The reasons for this are clear. The lightest neutralino in this region of parameter space is too light, and the Z decay width becomes too large. The truncated section in the lower right corner has a straightforward explanation as well. Here the stop is always lighter than the lightest neutralino and therefore becomes the LSP, which we exclude.

It is very interesting to see the effect of supersymmetry on other observables. In Figure 2 we plot three observables, R_b, M_W, and A_{LR} versus the lightest chargino mass. The dotted line in each graph is the central measured value of each of these observables, and the dashed lines are the 1σ errors associated with the measurements. The measured value for R_b is taken from Ref. [7], M_W from [23], and A_{LR} from [24]. The solid straight line is ZOPOLE's best fit Standard Model value with m_h fixed at $100\,\text{GeV}$ (the Standard Model values would disagree more with experiment if $m_h \gtrsim 300\,\text{GeV}$). The shaded region is the range of values

obtained (versus lightest chargino mass), as other parameters vary, which yield a better χ^2 with light superpartners and $\alpha_s(m_Z^2) = 0.112$ than the best χ^2 in the Standard Model.

Several aspects of Figure 2 are important. The R_b region is significantly higher than in the Standard Model. M_W is also higher. It is amusing that earlier values of M_W would have preferred the Standard Model to supersymmetry, but the new value [23] $(80.33 \pm 0.17\,\text{GeV})$ does not. The SUSY A_{LR} value is closer to the SLC A_{LR} measurement. These results translate to $\sin^2 \theta_W = 0.2312 \pm 0.0004$. The values of M_t that we found with $\chi^2_{SUSY} < \chi^2_{SM}$ range between $162\,\text{GeV}$ and $190\,\text{GeV}$. The upper limit on M_t comes about mostly from the inability to get low $\tan\beta$ and high M_t simultaneously, and still keep the top Yukawa perturbative at the high scale. With very light charginos we run the risk of having top decays into the lightest stop and light neutralinos be too numerous to be consistent with top quark production and decay data at Fermilab [25]. Figure 2 shows that the branching fraction of these supersymmetric top decays can be as high as 60%, and in general much of the parameter space has a significant top decay branching fraction into supersymmetric states which could be detected when many more top events are detected at a high luminosity collider.

It should be re-emphasized that the most important phenomenological implication of lowering the extracted $\alpha_s(m_Z^2)$ is light superpartners. Most of the allowed parameter space in Figure 1 will be detectable at LEP II and an upgraded FNAL collider. With sufficient luminosity LEP II will be able to detect all charginos and stops with masses to within a few GeV of $\sqrt{s}/2$. An upgraded Tevatron collider should be able to reach charginos and stops with considerably higher masses [26] than LEP. However, FNAL, and to a limited extent LEP, has some difficulty cleanly detecting a signal for Higgsino-like charginos. In the limit of pure Higgsino the LSP mass gets closer and closer to the lightest chargino mass. When the chargino decays into LSP plus leptons, the leptons may have too little energy to trigger on, so the signal is reduced. This region of chargino parameter space is largely the region we are in.

Conclusion

We have demonstrated that the extracted value of $\alpha_s(m_Z^2)$ from LEP/SLC data can be lowered to agree with other $\alpha_s(m_Z^2)$ determinations when superpartners are added to the fit. An essential aspect of this work is the inclusion of all relevant LEP/SLC data, so that the results are known to be consistent with all observables. We have found that light charginos and stops (with masses below $\sim 100\,\text{GeV}$) are required if the total χ^2_{SUSY} with

$\alpha_s(m_Z^2) = 0.112$ is better than the χ_{SM}^2 with $\alpha_s(m_Z^2)$ at its Standard Model best-fit value of 0.123. Our approach is largely independent of SUSY assumptions.

The SUSY spectrum and couplings required to obtain our results cannot be obtained in a fully minimal supersymmetric model. They can be obtained by adding the effects of high scale thresholds, and/or Planck scale operators, and/or perturbatively valid intermediate scales. It is very encouraging that data at the electroweak scale seems to be telling us about physics near the Planck scale.

The resultant supersymmetry parameter space has several important phenomenological implications: The W mass is higher than the expected Standard Model best fit. R_b and A_{LR} should also be larger than their Standard Model values. Light superpartners below about $100\,\text{GeV}$ must exist. LEP II and FNAL will probably find these superpartners if they are this light; if they don't, very precise determinations of the W mass, R_b, or A_{LR} could rule out or further support this exciting possibility.

Acknowledgements

References

[1] M. Shifman, Mod. Phys. Lett. **A10** (1995) 605.

[2] For example, see Fig. 6 in B.R. Webber, hep-ph/9410268.

[3] See for example, M. Voloshin, hep-ph/9502224; C. Davies, K. Horbostel, G. Lepage, A. Lidsey, J. Shigemitsu, J. Sloan, Phys. Lett. **B345** (1995) 42.

[4] L. Clavelli, hep-ph/9410343.

[5] J. Erler and P. Langacker, hep-ph/9411203.

[6] J. Bagger, K. Matchev, and D. Pierce, Phys. Lett. **B348** (1995) 443.

[7] The LEP Collaborations and the LEP Electroweak Working Group, CERN/PPE/94-187.

[8] G. Kane, C. Kolda, L. Roszkowski, and J. Wells, Phys. Rev. **D49** (1994) 6173.

[9] P. Langacker and N. Polonsky, Phys. Rev. Lett. **47** (1993) 4028.

[10] P. Langacker and N. Polonsky, hep-ph/9503214.

[11] P.H. Chankowski, Z. Pluciennik, and S. Pokorski, Nucl. Phys. **B439** (1995) 23.

[12] R. Barbieri and L.J. Hall, Phys. Rev. Lett. **68** (1992) 752.

[13] L. Roszkowski and M. Shifman, hep-ph/9503358.

[14] E. Witten, Nucl. Phys. **B258** (1985) 75; A. Brignole, L.E. Ibáñez, and C. Muñoz, Nucl. Phys. **B422** (1994) 125 (Erratum-ibid, **436** (1995) 747).

[15] S.P. Martin and P. Ramond, hep-ph/9501244.

[16] For a review of $\alpha_s(m_Z^2)$ determinations at LEP and SLC, see S. Catani, hep-ph/9411361.

[17] See also L. Clavelli and P.W. Coulter, Phys. Rev. **D51** (1995) 1117.

[18] S. Brodsky and H. Lu, SLAC-PUB-6389.

[19] K.A. Clay and S.D. Ellis, hep-ph/9502223.

[20] B. Kniehl and R.G. Stuart, Comp. Phys. Comm. **72** (1992) 175.

[21] F. James and M. Roos, Comp. Phys. Comm. **10** (1975) 343.

[22] J. Wells, C. Kolda, and G.L. Kane, Phys. Lett. **B338** (1994) 219.

[23] K. Einsweiler, Talk at the 1995 APS April Meeting, Washington, D.C.

[24] The SLD Collaboration (K. Abe et al.), SLAC-PUB-6456.

[25] The CDF Collaboration, FERMILAB-PUB-95-022-E (February 1995).

[26] S. Mrenna, G.L. Kane, G. Kribs, and J. Wells, UM-TH-95-14.